Provisional conclusions about hierarchical organisation in complex systems

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This panorama of hierarchical organisation in social and natural sciences was intended to improve our understanding of universally emerging hierarchical organisations in nature and society. We expected new insights from the analysis of the scope for circulating concepts and methods between various disciplines. We were searching for a possible general explanation for hierarchical structures. We have reviewed a whole set of quantitative and qualitative approaches, including measures and analytical tools, which provide deeper knowledge about general and specific processes generating or maintaining hierarchies. But this theoretical and methodological investigation has also led us to reverse the question, through the discovery of a possible explanatory power of hierarchical structures themselves, as a necessary part of the architecture of complex systems. Looking for hierarchical organisation would thus become an essential methodological step in the description and understanding of complex systems.

Hierarchy as a concept related to legitimacy

A first general explanation for the universal appearance of hierarchies in the social world is their connection with power and legitimacy. A review of the usage of the word hierarchy in dictionaries and scientific literature up to the end of 19th century by Nicolas Verdier demonstrates the long-standing strong link of this usage with the religious institutions. Reference to a "natural" order of social standing established upon divine right is common to several cultures. According to Max Weber, there were three sources for the legitimacy of political power in the history of societies, firstly reference to the sacred, secondly charismatic influence, and thirdly legal and rational standards of efficiency. Social hierarchy expresses a social order by reference to a collective system of beliefs that legitimises these sources of power. Hierarchy is still today a recognised procedural method for establishing decisions that are considered as right and legitimate. For instance, this methodological device is encountered in the pyramidal organisation of legitimate sources in Muslim law, from *Coran*, then *sunna*, to *ijmsa* (or consensus) and *qiyas* (analogy). In the Roman legal system, there is also a hierarchy of standards, each rule at the lower level having to be compatible with the upper levels (for instance, from a constitution to laws, rules and decrees in French, Spanish, Greek or Italian legal systems today). The consistency between the general order and the particular cases is governed by a set of nested rules subordinated by their succession in a hierarchical order. (There are however other legal systems, like "common law", where the hierarchical principle is not present to the same extent).

Since it is conventional in upholding the legitimacy of social rules, hierarchy could appear as a mere matter of social representation. Some archaeologists claim that the process of « verticalisation » of the mental image of the world, whereby the human species thinks of itself as dominant, occurred before the Neolithic revolution, at the time of animal domestication (around 10 000 BC), in the Middle East and the Euphrates valley. The invention of domestication could denote an alteration in mindset, placing humankind above the other components of nature, with which it previously entertained horizontal relationships. This new consciousness of domination, in the form of a vertical hierarchy, is sometimes considered as a cognitive revolution that could have preceded technological change, and could have been a necessary condition for its emergence. However, observers of animal behaviour have noticed that hierarchies, demonstrating strict or partial order, exist within a number of animal societies, in a broad variety of forms. Hierarchy is sometimes thought to confer an adaptive advantage, as it provides a non-violent solution to conflicting situations, even if in most cases it is established after a fight.

Nicolas Verdier analyses the transition between the theological acceptation of a strict ranking order and the more multidimensional social usage of the word hierarchy, which only appeared during the 19th century, after the disappearance of the Ancient Regime. Quoting Voltaire: “different hierarchical ranks are strictly incommensurable”, he also emphasises the increasing neutralisation of the word accompanying the growing social rejection of hierarchical structures (for instance with Tocqueville assimilating hierarchy to despotism). This evolution is parallel to the transition of societies from agrarian economies towards more complex modes of production that cannot be represented by the simple distinction between peasants, priests and soldiers. Both the recognition that social orderings are many and various, and the general suspicion attached to the hierarchical social structures in democratic systems, could explain why contemporary sociologists do not often refer to social hierarchies (for instance social hierarchy is merely a matter of stratification for Parsons), even if the principle remains very often as an implicit or commonplace fact in their analyses (see below). This “historical-genetic derivation” (according to the terminology for the “styles of scientific thinking” developed by A.C. Crombie, 1994) of the successive meanings of the word hierarchy by Nicolas Verdier shows us that great caution is required when looking at the social historical significance of the word. We cannot assume that the word retains the same connotations over time, even if the early meaning still probably contaminates its contemporary usage.

Functional social explanations of hierarchy

Even if it is open to question that hierarchy mainly reflects the organisation of our minds, it is true that it does emerge in a large variety of social situations. We have not devoted a chapter to the presentation of social hierarchies. Another book would be probably necessary for this purpose, since the question of social hierarchy is embedded in the various possible definitions of social status, social practices and social institutions to such extent that the work of sociology overall would have to be envisaged to describe how the concept of hierarchy operates in social contexts. New theories of the hierarchical organisation of society, disconnected from the previous legitimate order based on divine right, were conceived at the time when the democratic regimes and the political power of lay society were emerging in the western world. Among these theories that are intended to explain social order in industrialised societies three main types can be recalled: 1) the notion of social class, perhaps invented by Turgot, and based by Marx upon the appropriation of production means, as reflecting the domination by capitalists over proletarians, although the class of landowners was not easy to position in a strict order in relation to these two main classes; 2) a functional model was conceived by Kingsley Davis and Wilbert Moore to explain social hierarchies by the functional importance of jobs in the division of labour, according to the duration of job training and labour availability in the relevant employments; 3) the market model, as suggested by A. Smith, based upon the same principles, but it postulates, instead of a necessary regulation process reproducing the division of labour across generations, an equilibrium between supply and demand in each type of job, according to multiple criteria. W.Pareto’s theory of the circulation of elites belongs to the same liberal model.

In a systemic view, social hierarchies are the product of social interaction, which also contributes to maintaining them. They rely upon a two-way circulation of information. The social order conveying authority, power and control follows a top-down line, while admiration, respect and obedience move from bottom up. However, especially in modern societies where the division of labour has become more and more complex social hierarchies never follow a simple ordering, they use multiple dimensions which are often highly correlated but not fully redundant, like prestige, power, income, material and symbolic gratifications (capital, cultural capital, social capital in contemporary terms). Even in traditional social orders, for which G. Dumézil was able to develop a three-function theory (the priests, the soldiers and the peasants, with uncertainty about the ranking of merchants) from a comparison of all Indo-European societies, it was noticed that the social hierarchy could be more or less strict, as Louis Dumont recognised by contrasting the marked holistic hierarchy of castes in Indian society (as described in his book *Homo hierarchicus)*, with the *homo equalis* of western societies where individualism is preponderant. After considering that society is made up of different groups separated by blurred demarcation lines and organised into a hierarchical order, contemporary sociology thinks in terms of social networks. Social relatioships between actors always involve asymmetrical shares of power, but they also require a reciprocal transfer of resources and implication on the part of the actors. Instead of being embedded in a nested order, the networks that these relationships generate have many intersections, and they are not all of the hierarchical type, but display various models of possible spatial interaction. As hierarchy is a particular kind of network, we can recall briefly the methods that are provided by network analysis.

Hierarchy and networks

The graph theory was for a long time the most widely used tool for the analysis of networks. A graph is a simplified representation of a network in which the nodes are "vertices" and the links are "edges". It is analogous to an interaction matrix. A graph without cycles is called a tree, and can represent any hierarchical organisation such as a river system or a pyramid of levels of responsibility in an army or a firm. This pure form is rarely observed in the social world. Graphs of social relationships exhibit many cycles, which are transitive relations from node a to b then c and back to a. It is these closed loops, which may involve more than three nodes, that are called cycles. The global connectivity of the graph is measured by different ratios comparing the number of nodes to the number of possible edges, and connectivity increases with the number of cycles in the graph. In classic applications of graph theory, various indices were also used to identify relative positions of nodes in the graph, in terms of relative accessibility to the other nodes. These measures of centrality are influenced by the number of direct paths that join one node to others. B. Gaume, F. Venant and B. Victorri (chapter 5) suggest more effective methods for analysing relative positions of this type, applied to a linguistic space defined by relationships of proximity between words (French verbs in their case) in terms of meaning. They resort to new means of analysis that were developed for social networks. Social networks are more complex than simple tree-like networks, because they include many cycles, but they nevertheless very often exhibit certain hierarchical features, since accessibility is not equally distributed within the network, in contrast to regular lattices. Nor is it distributed randomly around a mean, as in the classic Erdös-Renyi model, but on the contrary has a very large variance, a few nodes having many connections while many others are poorly connected. When the number of connections per node is distributed according to a Pareto law, the network is called "scale free". This denomination refers to the absence of any significant average in the distribution, and thus absence of any characteristic scale. In social terms, this means that the centrality (or "betweenness") is very unequally distributed within the network. Scale-free networks can reveal a "spontaneous" hierarchical ordering in society. For example, western societies and their tentacles in the era of globalisation have recently made a wide-scale experiment in creating a large network with the diffusion of Internet. Many dreamed of an equal, ubiquitous access to this new medium for circulation of information, often presented as the most democratic tool ever invented. However, analytical studies of the structure of the network have revealed that it is very unequal in terms of numbers of connections available to each node: the structure is hierarchical and similar to the model for "scale-free networks" constructed by Barabasi and Albert (1998).

B. Gaume, F. Venant and B. Victorri (chapter 5) demonstrate that semantics in natural language is organised in the same way as social networks. Some words have many close synonyms, while other more precise terms are isolated. Each word can be characterised by its number of connections with others and this distribution is highly hierarchical. In fact the structure of the graph of semantic relationships is similar to networks that were identified as "small worlds" (Watts and Strogatz, 1998) because, besides their hierarchical structure (where the distribution of the degree of the nodes follows a power law, according to a scale-free topology), they also present marked clustering (many cycles in the graph) which is paradoxically combined with a rather low value for the diameter of the graph (the diameter is the length of the maximum topological separation between any pair of nodes). The diameter of a graph gives an idea of the efficiency of communication between its parts. For a network of N nodes, the diameter is about log N in the case of a small world, (that is, 6 for one million of nodes) while without that modular organisation the diameter is around the square root of N (that is, 1000 for one million nodes). Marked clustering and hierarchical organisation thus facilitate the circulation of information within this type of network, which is frequently observed in social contexts. Efficiency in conveying information has long been the main rationale for explaining the prevalence of hierarchical organisation in human activities.

Instead of restricting themselves to enumerating the degree of a node as a measure of its centrality, or hierarchical position, within the network, B. Gaume, F. Venant and B. Victorri suggest two complementary tools: the "global k proxemy" which measures the centrality of a node after its position within regions that are more or less densely linked in the graph (in the neighbourhood of dimension k), and a measure based on the number of "cliques" (or cycles comprising various numbers of nodes) which provides similar results. These methods could be applied to other types of networks, as they identify a complex hierarchy among the nodes by classifying them at different levels, according to local measurements of centrality.

Concepts from graph theory or analytical tools linked with the notion of small worlds and scale-free networks are however not entirely satisfactory for describing social networks, since they miss the fact that they are very often oriented networks, with an asymmetrical signification of the relationship. Dynamic modelling of oriented graph structures is most often provided through simulation tools, which have become more and more powerful in the last decades. This is a shift from social explanation to the statistical simulation of hierarchies.

Hierarchical organisation or hierarchical differentiation

We are now entering a domain where a more formal description of systems, involving measurement and enumeration, will enable the application of methods that are transversal to a large number of disciplines. We therefore require common definitions. What is a hierarchical system? Before discussing statistical approaches to hierarchies, a distinction needs to be made between two possible acceptations of what hierarchical form in a system is. A hierarchy can be conceived as an ordered succession of distinct levels, that are more or less clearly separated, but that can be considered separately since the processes that are involved in the construction of each level are very often different from one level to the next. We suggest using the term *hierarchical organisation*, when different and more or less autonomous entities can be observed at different levels of observation, and when each level needs to be described with different attributes because new properties emerge at each level of organisation. Hierarchical organisation can concern *inclusive hierarchies*, as in the biological domain, where each level is embedded in the next, proteins in cells, cells in organs, organs in organisms, and so on. However, even in biology for the definition of species or ecological systems, and *a fortiori* in the social world, most hierarchical organisations are *heterarchies,* where the levels are less easy to identify and to separate: defining and delimitating a group, a social network, a class, a culture or a civilisation is neither simple nor obvious, even if different levels can be recognised and hierarchised according to the more or less broad generality, magnitude or scope within which they are operating.

The second acceptation is the view that hierarchy in a system can also be described as a continuum of differences in size, where the elements in the system are strongly differentiated, even if they retain the same appellation and the same collection of attributes according to their ontological definition. Many examples are to be found in astronomy (size of stars or galaxies) or in the social world, as for example in the case of urbanism: we still use the same word "cities" to refer to groups of resident population that are different by several orders of magnitude, since they range from a few thousand to tens of millions of inhabitants, and the weight of their economies ranges from the turnover of a very small artisan firm to gross urban products that are equivalent to those of powerful nation states (to give a few examples: it is estimated that the economy of the Tokyo urban area is equivalent in size to the gross product of France, the economy of New York weighs as much as China's economy overall, while Paris produces as much as the whole of the Netherlands). Another example of a continuous distribution of sizes including very large differences in terms of economic power and scope of activity is observed in the case of firms, when they are ranked according to numbers of employees or turnover. We shall use the expression *hierarchical differentiation* when referring to this type of hierarchical feature.

When applied to cities or firms, the expression *hierarchy of size* does not mean that there is any relationship of subordination, direct or indirect, between the smallest and the largest elements in the series, but that their capacity for action or their weight in a social universe of competence, decision and consequence, are of very different magnitude (Pumain, 2003). Because of these inequalities in potentialities and power, the former connotation of domination is however never very far, and the expression also often refers in an indirect way to the first acceptation of social hierarchies. Whatever these social connotations, this kind of hierarchical differentiation in the size of subsystems is always reflected in a specific type of statistical distribution, known as "highly skewed" or "long tail" distribution. Many models have been suggested for describing hierarchies of size, from the various "types" of distribution that Pareto applied to the distribution of income, to the applications of lognormal distribution to firms and cities by Kapteyn and Gibrat, as well as the so-called "Zipf's law". This is very similar to a Pareto distribution, but usually figured in a simplified way on a log-log plot of size of a subsystem against its rank (the rank is equivalent to the cumulated number of subsystems that are of larger size). What is of interest in relation to these statistical models is not so much to determine which is best suited to specific observations (since the exact measurement of size in a social universe is a delicate exercise, always including significant margins of error or uncertainties in delimitation of the subsystems) but to understand how these types of distributions are generated and maintained over time. The statistical model is not in itself an explanation, but gives incentive to search for plausible and meaningful processes that may be behind its general emergence. There is also a further plausible hypothesis which is that the generative processes, from the bottom to the top of the hierarchy, may be the same in situations that are found in natural as well as in social sciences.

The analysis of hierarchical differentiation in terms of power laws is based on a simplified formal representation of complex systems, as being observable at three levels of organisation at least: the Pareto distribution of subsystem sizes is a characteristic property of the system at the macro level; This system can be broken down into subsystems (forming the meso-level) whose size is measured according to the number of elements (forming the micro-level). The identification and specification of subsystems is however a very delicate task in the realm of social sciences at least. Can we consider that a social network, or a firm, or a city, belong to the same kind of entity irrespective of size? Is it right to consider them as comparable entities whose differences can be summarised by their inequalities in size? The question remains open. On one hand, if this postulate is accepted, it is possible to gain insight into the generative process of hierarchical differentiation of this type by reviewing all the dynamic models that have been suggested for explaining highly skewed distributions, and to suggest a simple unifying statistical theory covering a large variety of systems. On the other hand, we shall see below that different rationales can be envisaged to explain hierarchical differentiation, by looking at the qualitative interaction between the elements that compose the subsystems. This will lead us to consider the possibility of using scaling laws to unify perspectives on hierarchical differentiation and hierarchical organisation in complex systems (see below).

Statistical explanation of Zipf's Law using random growth processes

Since Zipf, who suggested that his "rank-size" rule as applied to city sizes reflected an equilibrium between two forces, one of spatial concentration (of economic activities around markets) and one of dispersion (of raw material and resources), progress has been made by shifting from these static and intuitive explanations towards dynamic models that explain both the shape of the statistical distribution and its persistency over time. Even before Zipf, simple statistical growth processes were suggested as being able to generate "long tail" distributions of this type (for instance by Yule in 1924). The model proposed by the French statistician and economist Gibrat in 1931 to explain inequalities in economics establishes a clear connection, derived from the "law of large numbers" or central limit theorem, between a stochastic process of growth and the resulting lognormal distribution of sizes. The advantage of such a model is that its hypotheses can be tested onempirical examples. The main hypotheses are that in a short time interval, additional growth is proportional to the initial size (which is equivalent to saying that growth rates are on average the same), and that the fluctuations around the mean growth rate are independent of size, and independent from one period of time to the next. These hypotheses were tested and roughly validated on long-term series of urban populations by geographers like B. Robson (1973), or Pumain (1982) and Guérin-Pace (1995). Gibrat's model was recently rediscovered as a possible explanatory tool for Zipf or Pareto distributions by economists like Gabaix and Ioannides (2002). Its hypotheses have been used in a variety of simulation models.

However, even if simulations based upon random processes are able to reproduce hierarchical structures that have similar properties to the observed properties, it is very unlikely that such an explanation can be considered as final. First, it would mean accepting a purely statistical description, similar to the "empirical models" that R. Franck (2002) criticises for their lack of generality. Second, even when they are reified as "theoretical models", because they are formal, very general and transposable, the stochastic models that generate hierarchies through random growth processes are mainly operational models. They allow some predictions through projections. They provide a dynamic interpretation of the statistical shape of the hierarchies. But they neglect an essential feature of the emergence and maintenance of hierarchies in social systems, which is social interaction. Where the task is to summarize thousands of interactions using the “law of large numbers”, the many independent causes that lead to differential growth, in social entities like firms or geographical entities like cities and territories, social sciences (and those who use results to understand and take action) need to know what relationships, asymmetries, or regulations underpin what could appear at a global level to be produced randomly.

Cellular automata for spatial simulation

Cellular automata are regular lattices that are used in simulation models where various types of neighbouring effects or spatial interaction can be introduced, in the form of rules that interfere with the evolution of each cell (cells representing localised objects or agents). M. Batty (chapter 6) applies a deductive method for a bottom-up construction of urban systems, using cellular automata for the generation of the spatial distribution of more or less densely populated settlements. He proposes a stepwise construction of more and more realistic distributions, starting with a simple stochastic model of population growth, such as Gibrat’s model generating lognormal distributions of population sizes. He demonstrates that if a growth process following a random walk with a reflecting barrier can generate a lognormal or Zipf distribution, this model produces inconsistencies when compared to observed trajectories of individual cities: changes in population size are slower and there is more inertia in the real world. Unlike the economic model suggested by Gabaix, which uses the agglomeration economies principle to justify an application of Gibrats’ model, M. Batty proves that introducing spatial interaction is a necessary condition for a plausible generative process for urban settlements: “there is a deep underlying rationale for the existence of rank-size distribution which is essentially a spatial or geometric ordering in the geographical sense”. A positive spatial auto-correlation in growth rates (representing a local diffusion model), that links the growth in a cell with that of its neighbour cells, provides better results in the simulation. This method is analogous with the principle of “preferential attachment” that is suggested by Barabasi for generating “scale-free networks” (Barabasi and Albert, 1998). It is also allied to former explanations of urban hierarchies that interpreted them in terms of “central” urban functions, linking the size of a city’s population to the number and diversity of services it provides for a surrounding area of varying magnitude. Far from the rigid geometries first imagined by W. Christaller, the “inventor” of central place theory, M. Batty suggests that overlapping hierarchies, corresponding to various types of interlocking networks connecting different urban activities, could give a better model for a comprehensive explanation of urban systems. He also wonders how the knowledge about possible generative processes of real-world hierarchies could be used in design and planning of more efficient or sustainable ways of locating activities and their possible interactions.

Inclusive hierarchies in biology

Possible rationales for embedded or inclusive hierarchical organisations can be suggested by analysing biological entities. Alain Pavé (chapter 2) follows two main lines of inquiry, in an attempt to explain our representation of hierarchically embedded systems and of a time-organised phylogeny of species. He sets out the definition of a variety of hierarchical levels that can be distinguished, from sub-cellular systems to ecosystems, identifying characteristic times and scales for each of them, as well as interaction processes that are essential in their generation. He emphasises that co-operative mechanisms should be considered to be as important as competitive mechanisms to explain “the global biological organisation from genes to ecosystems and biosphere” as well as “the actual embedded hierarchy of organised entities and trophic networks”. There is also a mix of stochastic and deterministic processes in the explanation of the hierarchical organisation. Reviewing a series of methods that can help in understanding these complex systems, he shows that computer-based models may be better suited for representing interactions and visualising structures than mathematical models, but to date there are too few theoretical results to validate those approaches. He therefore suggests an integrative modelling method for linking models of elementary processes involving well-known mathematical relationships to hierarchical levels of higher complexity. Thus better management tools adapted to deal with complexity could be derived through modelling and simulation.

Thus far, we are left with our initial question regarding the necessary existence of hierarchical organisations. In the biological world as well as in social situations, there is a general mystery: independent decisions unknowingly construct systems that could have being designed by engineers. Hierarchical organisations seem to appear as almost inevitable emergent phenomena in many natural and social contexts, but we do not know if they are occurring merely by chance, being configurations that have a high probability of occurring, (i.e. as a stable attractor in a very general or commonplace dynamic model), or if such configurations everywhere correspond to the optimisation of some principle – and in any event, the constraining principles need to be identified. Can we get deeper insight into this conception of self-organised criticality, which interprets hierarchies as organisations that are able to maintain their configuration within changing environments?

Scaling laws in physics and biology

A promising tool for a better understanding of the general emergence of hierarchies in the natural and social worlds is the construction of scaling laws. Scaling laws establish invariant relationships, which are in general non-linear, between quantitative measurements of various attributes over a wide range of sizes of individual entities. G.B. West (chapter 3) suggests that they could offer much better tools for comparison than the usual ratios (which assume mostly linear effects) that we spontaneously apply when comparing the attributes of objects that are very different in size. For instance, the “social indicators” that are used for comparing countries, cities, or firms of different sizes are simple ratios to size, for instance gross product per capita, or demographic rates. G.B. West suggests that more appropriate scaling methods provide a better judgment in such comparisons, as he demonstrates in the cases of evaluating the relative strength of ants and men, or sportsmen belonging to different weight categories. But another advantage of scaling laws is that they “typically reflect underlying generic features and physical principles that are independent of detailed dynamics or specific characteristics of particular models”. After underlining the similarities between the mathematical structures of the scaling of the fundamental forces in the quantum field theory and in biology, G.B. West recalls important results that have been obtained in biology, where scaling laws exhibiting universal quarter-powers are interpreted according to the “generic properties of the various hierarchical fractal-like branching network systems that sustain life at all scales” (for instance circulatory, respiratory, renal and neural systems and vascular systems in plants). Thus the connection between scaling laws and hierarchical organisation is very strong in physics and biology, and there is a “hint suggestive of a similar origin” to be found “in the observation that at all scales many biological structures exhibit hierarchical, fractal-like networks which are topologically similar to the tree-like hierarchies in the Feynman diagrams driving the scaling of the strengths of the fundamental forces”.

According to G. West, a human being survives with an energy consumption equivalent to one hundred watts, whereas if the cells that compose his or her organs were isolated *in vitro*, 10 000 watts would be required. Inclusive hierarchies that characterize the organisation of the living world are therefore very efficient in terms of energy consumption. There are indeed economies of scale in the use of energy that allowed the emergence of very large organisms in the course of biological evolution. This brings evidence that, rather than the metaphor suggested by H. Simon and discussed by D. Lane (chapter 4), inclusive hierarchies in biology are not merely collections of independent “Chinese boxes”, and that interactions between levels shape the whole hierarchical organisation. The scaling laws observed between metabolic rates and the size of organisms have been explained by the specific nature of the branching systems that channel the energy flows in these living bodies. According to G.B. West, the mathematical demonstration of the linkage between the universal scaling parameters (three quarters exponents) and the minimisation of energy loss seems to be a very general result that allows further predictions.

Scaling laws in society

Do scaling laws apply to social organisations? There is an interesting difference which can be noticed from the above experiments: in social systems, energy consumption, instead of decreasing, increases with development. At national (state), region or city level, energy consumption scales supralinearly with population size (which means that the scaling parameter is above one, while it is below one in the biological instance). Human concentration seems to create added value of a different type from the simple ability to survive under the constraints of the physical environment. Social purposes are obviously of a different nature and the historical trend towards an increase in the number and range of human activities seems to be supported as much as it is constrained by the extra energy expenditure incurred for their achievement. The corresponding expression from Anderson “more is different” needs to be viewed with a different meaning in the biological and social contexts (see the discussion by D. Lane, chapter 4). Societies obviously have to deal with energy and information as constraining factors that hamper their unlimited development, but they can also create and innovate to overcome these limitations.

Many other differences should be underlined, since social evolution is not driven by natural selection but by an intentional process of innovation. This can explain why the evolution rate of social structures is much more rapid and time scales very short when compared with those of natural evolution. However, the observed evolution in the social world rarely reflects any individual, or even collective intentions as they are expressed in the dominant values, beliefs, general representations or expectations, or even according to the informational resources that are available at a given period to a given society. The resulting structures are not always unwanted, undesirable or even “perverse” effects, but most often they are unpredictable and unexpected. Among the surprising emerging properties of many social structures, and especially in social networks, is the existence of hierarchies and scaling laws.

The most promising line of research for using scaling laws and detecting their related constraining principles in the dynamic exploration of social hierarchies is therefore to measure social attributes that support growth and innovation, and enable the development of larger and larger social entities and more and more complex societies. In this process, David Lane recognizes the essential role of the “scaffolding structures” that govern the shift from one structure to the next while facilitating the introduction of innovations.

Are hierarchies a result of randomness or optimisation ?

The idea that hierarchical organisations are so frequent because they optimise some function or principle reappears with recent work by physicists and biologists. But the explanation is no longer static: the organisation is not only the result of an intentional design following a top-down plan, it is also produced through bottom-up evolutionary mechanisms. Hierarchies cannot be considered as happening purely at random. In the living world, it seems highly probable that physical constraints, without imposing complete determinism, have widely influenced the selection of hierarchical organisations that minimise losses of energy while optimising the circulation of flows, or facilitate co-operation during the building of new organisms at a higher level during evolution. This also could be the case in the organisation of natural languages, for which the action of economy principles in the efficiency of communication seems to be recognisable. In the case of cities, the “tyranny of distance” remains the major explanatory principle of hierarchical organisations in geographical space, but the role of this effect has been continuously revisited by social institutions, which have used it in a conscious way. Similarly, the effects of competitive growth are so many and diverse that they can alternatively be considered as totally constraining, or absolutely random !

From the comparative review of work on urban hierarchies all over the world conducted by D. Pumain, (chapter 7) a first result is the rejection of randomness as a satisfactory interpretation. The explanation of the statistical distribution of city size by a static entropy maximisation process, suggested by L. Curry and supported by B. Berry in 1964, is incomplete, because it neglects the action of a constraint in producing the model. The stochastic model of distributed urban growth proposed by Gibrat, although it is dynamic and fits most observations rather well, is not a sufficient explanation either, since it does not pinpoint the interactions that are behind the dynamics it describes. In contrast to the hypotheses that are defended by authors from the “new economic geography” trend (like P. Krugman or Fujita), the existing configuration of urban settlements cannot however be considered as being the direct expression of any optimum or static equilibrium. A functional system of cities equilibrating their supply and demand in economic activities has no incentive for evolution. An evolving urban system can only be explained by evolutionary, historical dynamics, where the progressive diversification and complexification of human activities through innovation have played a large part in building and consolidating the urban hierarchies. This is in favour of the fact that, if we were to distribute the population over the surface of the earth today, it would not be relocated where it is at present: the configuration of the system at a given time does not correspond to what would be the optimal distribution for that time. What could be considered in a given economic context as the optimal size for a city is never actually achieved. Path dependency is an essential process in urban dynamics, since most cities proceed from villages, and large cities from small towns. During this evolution, constraints, especially through transportation speed set against space-filling trends, act on the system in a more or less continuous way, but the system is never in equilibrium. Moreover, it is its own dynamics (consisting in general expansion and competition between cities) that provide the most convincing explanation for the emergence and maintenance of its hierarchical structure (see below).

Hierarchical organisation and complex systems

For David Lane (chapter 4), as opposed to the inclusive hierarchy in biology (the “Chinese boxes” that H. Simon refers to), society can be formalised in terms of an “artefact-agent space” which is organised into levels that are not exactly nested but tangled to varying degrees, producing what he calls “heterarchies”. It is in this context that emergence can occur between levels of organisation: human organisation emerges more often between existing levels. These levels are sometimes separated, segregated into spatio-temporal scales, but this is not always the case. Lane identifies three main levels:

- at macro level, there are scaffolding structures that control the evolution of the system
- at meso level, there are competence networks that deliver the system functionality

- at micro level are the individual actors, the “interactors”

This perspective is different from the interpretation of market systems, which considers the macro level of the market as the result of interacting micro-individual agents only. The meso-level is essential, it is a fluid level, which represents historical flows of interactions, or traces of past exchanges, which are called network structures. The complexity of this organisation stems from the circulation of information between levels: the notion of “methodological individualism” is not suited to organisation of this sort, since all levels are needed to understand how each operates, because of the efficacy of interaction between levels. However, while in social organisation level hierarchies need not be strict inclusion hierarchies, it is not by chance that there are connotations of order, inclusion and control attached to this use of the term. There are probable similarities linking this kind of organisation and the emergence of the properties of resilience and adaptability that are characteristics of complex systems, both in social and natural worlds.

These hypotheses are supported by the theoretical framework suggested by Denise Pumain (chapter 7) for hierarchies in urban systems. In this framework, urban hierarchy becomes an essential feature in defining the ability of complex urban systems, not only to adapt to, but also to generate almost continuous and sometimes accelerated socio-economic change. The evolutionary theory for urban systems unifies the earlier central place theory, the conception of cities as nodes in global networks, the theory of innovation cycles and urban specialisation as well as the theory of hierarchical diffusion of innovation, within a conception of complex systems in which urban systems are viewed as adaptive tools for social innovation. Conscious political and economic processes as well as physical territorial and temporal constraints are integrated into the dynamics. The theory establishes conceptual links between scaling laws in the description of urban hierarchies, space-filling processes and social (technical, economic and cultural) innovation. A few ideas are put forward for a possible transcription of these qualitative propositions into mathematical models. Demonstration, as suggested by Alain Pavé for hierarchical systems in biology, has so far been provided using simulation models (multi-agent systems) such as the SIMPOP model. In its generic version, a model of this sort is able to reproduce the main structural and evolutionary properties of urban systems, as well as a variety of urban configurations as observed in different parts of the world.

While deepening our knowledge about the possible explanations for the universality of hierarchical organisations, we have improved our understanding of what makes systems robust and resilient. The secret of their persistent organisation lies in the complex networks that mediate social, biological and physical interactions on different spatial and temporal scales. Thus, two directions for future research seem promising: The first concerns improving the definition of abstract entities and measures for a better appraisal of the scaling laws that shape the hierarchical features in complex networks. Scaling laws, when appropriately designed, can reveal the processes that ensure the maintenance and evolution of the structure of a system. Second, instead of focusing research into emerging properties in complex systems on two-level modelling, where the macro-structures are assumed to be created by interactions at the micro-level, as in many agent-based or game theory models, greater attention should be paid to multi-level structures and the circulation of information between the levels. In a social sciences perspective, it has been frequently observed that many systems are much more resilient than the dynamic statistical models describing them would have predicted. This underlines the importance of research into the processes of social reproduction. Until the 1980s, such processes were relatively easy to document and formalise, by studying the mobilisation of information resources and their asymmetries in social networks. With the emergence of the so-called “information society”, including the domination of the economy by stock markets, the merchandising of information, the proliferation of large networks and the atomisation of property, without forgetting the new modes of governance that enhance participative instead of representative systems, it has become more difficult to identify the various institutions that maintain social order at meso-level by ensuring the circulation of information between levels. Although deliberately dissimulated or difficult to detect, the hierarchical patterns that operate in new networks are being brought into the open by economists or political scientists interested in regulation processes or institutions, in an evolutionary perspective.

We have thus reversed our initial challenge: in endeavouring to find methods to gain a better understanding of the emergence, universality and durability of hierarchical organisations, we can now suggest using these hierarchies as methodological tools, as significant markers, or detectors, of the operation and evolution of complex systems. This perspective will perhaps help us in solving the mystery of hierarchical organisation, which can still be considered as a commonplace or unexpected feature, but which in the light of this new perspective becomes highly meaningful. It invites further collaboration between sciences of natural and social complex systems, and this research could perhaps be considered as a first step in building a science of complex systems.

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